Power Management System

Field of the Invention

This invention relates to a power management system and more particularly to a
5   power management system for the supply of power to an implantable medical device,
such as an implantable hearing prosthesis. Even more particularly, it relates to a power
management system using a plurality of rechargeable batteries and for controlling the
use of the batteries by the prosthesis.

10 Background of the Invention

Implantable medical devices, such as cochlear implants, middle ear implants,
FES systems and the like, typically consist of two components, one part being an
external component commonly referred to as a processor unit and the other part being
an implanted internal component commonly referred to as a stimulator/receiver unit.
15 Traditionally both of these components cooperate together to provide a desirable
therapy to the implantee. In the case of implantable hearing prosthesis such as cochlear
implants and/or middle ear implants, the external component has consisted of a
microphone for detecting sounds, such as speech and environmental sounds, a speech
processor that converts the detected sounds and particularly speech into a coded signal,
20 a power source such as a battery and an external antenna/transmitter.

The coded signal output by the speech processor can be transmitted
transcutaneously to the implanted stimulator/receiver unit situated within the head of
the implantee. The transmission can occur through use of an inductive coupling
provided between the external antenna transmitter and an implanted antenna/receiver
25 which forms part of the stimulator/receiver unit. The communication serves to transmit
the coded sound signal and to provide power to the implanted stimulator/receiver unit.
The external part is generally worn outside the skin and can be positioned behind-the-
ear like a traditional BTE hearing aid and contains the components mentioned
previously.
30 The implanted stimulator/receiver unit typically includes the antenna/receiver
that receives the coded signal and power from the external processor component, and a
stimulator that processes the coded signal and outputs a stimulation signal to an
assembly, which applies the stimulation to generate the desired therapy. In the case of a
middle ear implant, the assembly may include a mechanical or hydromechanical

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actuator device that is coupled to the ossicles of the middle ear or directly to the inner ear for applying direct stimulation thereto, producing a hearing sensation corresponding to the originally detected sound. In the case of cochlear implants, the assembly may include an intra cochlear electrode assembly, which applies electrical stimulation directly to the auditory nerve producing a hearing sensation corresponding to the original detected sound. The implanted unit is located under the skin inside the mastoid and contains primarily means to demodulate or decode the signals transferred through the skin to drive an actuator or an electrode array and to convert the power transferred through the skin into an electric supply voltage. In known systems the implanted portion does not contain any independent power source and consequently the transcutaneous link must be in place and therefore the wearer must wear the external component permanently, which impedes the comfort of the wearer.

Due to other particular problems with the external components of existing hearing prosthetic devices, such as the aesthetics associated with wearing a visible external device, the wearer having to remove the device while showering or engaging in water related activities, and the likelihood that the alignment between the external and internal coils will be lost due to movements during sleep or physical activity, there exists a need to provide a system that allows for total freedom with improved simplicity and reliability. Consequently research has been directed to fully implantable hearing prosthetic systems that do not require external componentary for the operation thereof. This would include providing a medium-to-long term power source such as rechargeable batteries, in the implants to overcome the need for power to be continually transmitted to the implant from an external power source.

However certain challenges appear with providing implanted devices with such implanted power sources. Unlike ceramic capacitors used as present-day short-term energy reservoirs, a rechargeable battery degrades irreversibly during its lifetime. They can only undergo a particular maximum number of recharging cycles before the battery performance diminishes to a level where the battery is essentially unusable. The degradation is due to the decomposition of the electrolyte and due to electrode corrosion. The decomposition of the electrolyte can cause the generation of side products like hydrogen and other gases that tend to build up pressure in the battery enclosure and finally escape through flaws in the enclosure. Corrosion of electrodes leads to a reduction of the active surface area and may ultimately, if the battery continues to be charged and discharged, cause a short circuit inside the battery through

metal spikes growing from one electrode to the other. Both effects lead to a reduction of the available battery capacity and ultimately to total failure. In the worst case, the implanted battery may rupture causing a severe threat to the health and well being of the wearer. Furthermore, if rechargeable batteries are discharged before being fully

5   charged or conversely charged before being fully discharged, their overall capacity may be prematurely reduced.

Totally implantable hearing systems require a substantial amount of energy to be stored since the whole signal processing unit and supporting functions have to be supplied for a reasonable period of time. In order to be commercially viable, the

10   required battery life per charge is generally considered as being in the order of a week. On the other hand, the number of recharging cycles of a storage battery is limited. Thus the capacity and ultimate size of an implanted battery must be made as large as possible. However, such application of large batteries causes further challenges, including that they require thick enclosures, that is considered dead space, in order to

15   retain the pressure of evading gases. Large batteries are also prone to the occurrence of internal short circuiting and battery failures are due to their larger surface area. Furthermore, the larger the battery is, the more severe the thermal effect of a battery failure causing accumulative thermal damage to surrounding tissue.

It is desired to overcome, or at lease ameliorate any one or more of the

20   shortcomings of prior arrangements.

Summary of the Invention

According to a first aspect of the invention there is provided a power management system for supplying power to an output circuit comprising:

25   a plurality of rechargeable batteries;

first conversion means for converting a supply voltage to a battery voltage to enable charging of one or more of the plurality of rechargeable batteries; and

switch means to enable a selected battery from the plurality of batteries to be connected to the output circuit to enable the selected battery to be discharged through

30   the output circuit.

The switch means may also be connected to the first conversion means to enable charging to the selected battery. A battery from the plurality of rechargeable batteries may be selected one at a time to provide charge to the output circuit. The system may further comprise a second conversion means connected between the output circuit and

the switch means for converting the voltage of the selected battery to a voltage for use by the output circuit thereby discharging the selected battery. The first conversion means may also act as the second conversion means in that charging and discharging of any one of the rechargeable batteries is performed through the same conversion means.

The switch means may comprise a plurality of switches, each switch in the plurality of switches connecting a respective battery to the first conversion means and to the output circuit. The system may further comprise a control unit for controlling the switch means to either enable charging or discharging of a rechargeable battery. The system may further comprise multiplexer means having an input connected to one terminal of each battery to enable the voltage signals pertaining to each battery to be selected and forwarded to an analogue to digital converter.

The system may further comprise shunt impedance means connected to the other terminal of each battery to measure the charge current or discharge current of each battery, represented as a voltage drop across the shunt impedance means. The shunt impedance means may be connected in parallel to a shunt switch to short circuit the shunt impedance means when not in use.

The system may further comprise amplification means connected between the shunt impedance means and the multiplexer means to amplify the voltage drop across the shunt impedance means to the input voltage range of the analogue to digital converter. The analogue to digital converter may measure individual battery voltage of any one of the rechargeable batteries in the plurality of rechargeable batteries and may convert the measured voltage to a digital value. The analogue to digital converter may measure the voltage drop across the shunt impedance means and convert the measured voltage into a digital value.

The system may further comprise a register for storing information pertaining to each battery. The information may comprise any one or more of charge status of each battery, error status of each battery and a flag indicating whether a battery has been disabled from being charged or discharged.

The control unit may be in communication with the register and the analogue to digital converter for processing signals and data from the analogue to digital converter and from the register. The control unit may periodically sense the presence of a voltage at the input to the switch means. The control unit may select a battery to be charged or discharged on the basis of information stored in the register pertaining to a particular battery.

The second converter means may enable discharging of a battery such that charge in the selected battery is forwarded to the output circuit. The output circuit may form part of a medical prosthesis. Preferably the prosthesis is an implantable hearing prosthesis such as a cochlear implant or middle ear implant. The first conversion

5 means may include an inductive means, one or more switch means and a switch control unit to enable charging and/or discharging of a rechargeable battery. The second conversion means may include an inductive means, one or more switch means and a switch control unit to enable discharging of a selected rechargeable battery. The supply voltage may be derived from an inductive means and rectified into a direct voltage to

10 be applied to the inductive means of the first conversion means.

According to a second aspect of the invention there is provided a method of managing the supply of power to an output circuit in a system that includes a plurality of rechargeable batteries, said method comprising the steps of:

converting a supply voltage to a battery voltage to enable charging of one or

15 more rechargeable batteries of the plurality of rechargeable batteries; and

connecting one of the batteries in the plurality of rechargeable batteries, using switch means, to the output circuit to enable the connected battery to be discharged through the output circuit.

The method may further comprise the step of converting the voltage output from

20 the connected battery to a voltage for use by the output circuit.

The method may further comprise the step of providing the switch means in the form of a bank of switches, one for each rechargeable battery.

The method may further comprise the step of controlling the switch means to enable the charging or discharging of a selected battery on the basis of information

25 stored in a register on each of the rechargeable batteries. It may further comprise multiplexing and measuring parameters, such as battery voltage, battery charge and battery current pertaining to each rechargeable battery for storage as digital values in the register.

The method may further comprise maintaining a record in the register of the

30 state of charge of each rechargeable battery. It may further comprise providing an optimum range, as a percentage value of the state of charge, within which each rechargeable battery is charged and/or discharged. Where the charge of a battery is above a first percentage limit of the state of charge of that battery, the method may further comprise the step of disabling charging of that battery. Where the charge of a

battery is below a second percentage limit of the state of charge, the method may further comprise the step of terminating the discharging of that battery.

The method may further comprise a means to flag out a battery which was judged as being defective by failing the check for consistency between cell voltage, 5   current and state of charge being determined for each individual battery and to supersede this specific battery for future charging and discharging operations.

Brief Description of the Drawings

Preferred embodiments of the invention will hereinafter be described, by way of 10   example only, with reference to the accompanying drawings, wherein:

Figure 1 is a block diagram of a power management system for supplying power to an output circuit according to a first embodiment of the invention;

Figure 2 is a timing diagram showing the charging of two batteries, from a plurality of rechargeable batteries, in the power management system of Figure 1;

15   Figure 3 is a timing diagram showing the discharging of two batteries from a plurality of rechargeable batteries in the power management system of Figure 1;

Figure 4 is a block diagram of a power management system for providing power to an output circuit according to a second embodiment; and

Figure 5 is a timing diagram showing the charging and discharging of 20   rechargeable batteries in the power management system of Figure 4.

Detailed Description of the Preferred Embodiments

With reference to Figure 1 there is shown a block electrical circuit diagram of a multiple battery power supply particularly adapted for an implantable hearing 25   prosthesis such as a cochlear implant, a middle ear implant or a hydromechanical inner ear stimulator. It primarily consists of first conversion means in the form of an input voltage converter circuit 5, second conversion means in the form of an output voltage converter circuit 7 and an array of rechargeable batteries 6. An induction coil 1 detects and picks up varying magnetic fields from primary induction coils brought into 30   proximity with the coil 1 and delivers an induction voltage at its terminals. Power transfer at a specific frequency can be made more efficient by optionally including the induction coil in a resonant circuit whereby a capacitor is connected in parallel or series to the coil 1. A rectifier 2 rectifies the AC voltage generated by the coil 1 or in other words converts the induction voltage into a DC voltage. The rectifier is shown as a full

wave rectifier, however other embodiments such as half wave rectifiers or voltage doubling rectifiers can be used. A charging capacitor 3 removes the ripple of the rectified voltage delivered by the rectifier 2 and a voltage limiting device 4 absorbs excess voltage generated by the coil 1. After passing through the capacitor 3 and

5   voltage limiting device 4, the DC voltage is passed to the input voltage converter circuit 5 which is preferably a step-down (or buck) type. It converts the voltage into an appropriate voltage to charge rechargeable batteries B_1, B_2 up to B_n. The input voltage converter circuit 5 is primarily made up of a charge switch 5a, an inductor 5b, a discharge switch 5c and a switch control unit 5d. The switch control unit 5d provides

10   control signals to switches 5a and 5c as a function of the desired charge current and saturation current of the inductor 5b. The array 6 of rechargeable batteries comprises one rechargeable battery B_1 and at least one further rechargeable battery B_2 of the same cell chemistry and size. The number of individual batteries is arbitrary. Associated switches S_{11}.... S_{n2} are included in a switch matrix that activates current paths from

15   specific batteries to the input voltage converter circuit 5 and the output voltage converter circuit 7 respectively. The output voltage converter circuit 7 converts the voltage of the rechargeable batteries B_1... B_n into a voltage appropriate to supply an output circuit (not shown) such as the circuitry of an implant, like as a middle ear implant or cochlear implant. If a specific battery is connected to the input voltage

20   converter 5, any other switch connecting a battery to the input voltage converter circuit 5 is inhibited in order to avoid parallel connections of batteries. This applies also to the output voltage converter circuit 7 respectively. Connected to each one of the batteries B_1... B_n between the positive terminal of each battery and its associated switch is a multiplexer 8. The output of the multiplexer 8 is linked to an analogue to digital

25   converter circuit 9 which in turn is linked to a control unit 10. The multiplexer circuit 8 enables each individual positive terminal of the batteries B_1... B_n to be switched to the input of the analogue to digital converter 9 or alternatively the positive terminal of a shunt resistor 12 connected between the negative terminal of each battery and ground may be directly connected through the multiplexer 8 to the converter 9. The analogue

30   to digital converter 9 measures the analogue battery voltage of each individual battery and converts it into a digital value which is then supplied to the control unit 10. Alternatively the analogue voltage drop across the shunt resistor 12 is converted into a digital value as well. The control unit 10 processes signals and data received from the converter 9 and a battery status register 11. The register 11 stores the charge and error

status of each individual battery in the array of rechargeable batteries. The control unit 10 thus periodically checks for the presence of a DC voltage at the input of each of the batteries (or corresponding switch) and enables the charging of the batteries by activating the various switches in the switch bank. Preferably, charging is enabled at state of charge (SOC) at or below the preset working regime of a used cell chemistry. For example, this pre-set working regime can be between 15% and 95% SOC for nickel metal hydride (NiMH) or between 0% and 80% SOC for graphite/lithium cobaltate cells. The cell chemistry of the batteries determines the charging characteristics applied by the control unit 10. By periodically scanning the voltage and current condition of each individual battery it keeps a record of their SOC, where a fully charged cell has 100% SOC, in the battery status register 11. The control unit 10 can be parameterised in order to support different cell chemistries, for example NiMH or nickel cadmium (NiCd) at 1.2V, Li-Ion (graphite/lithium cobaltate 4.2V, lithium titanate- lithium manganese spinel 2.3V) and various cell sizes. It should be appreciated that the cell chemistries and working regimes mentioned above are illustrative examples only and it is envisaged that any suitable implantable battery is included within the scope of the present application, such as solid state systems based on the lithium ion battery or "rocking chair" principle or any other suitable implantable battery based on currently unknown chemical composition. On similar grounds, working regimes which may turn out to be more favourable under certain circumstances are included within the scope of the present application.

The charge current of each individual battery is measured as a voltage drop across the shunt resistor 12 and integrated over time. Thus the resistor 12 generates a voltage drop proportional to the charge/discharge current of each individual battery. The integrated charge for each individual battery is held in the battery status register 11 whose bit vector represents the SOC. If the SOC of the battery is above the optimum regime, for example a first percentage limit, the charge process for this battery is disabled and shown as a flag in a battery disable flag field in the register 11. A switch 13 is used to bridge the shunt resistor 12 if not used and a scaling amplifier 14 amplifies the voltage drop across the shunt resistor 12 to a voltage appropriate to the input voltage range of the analogue to digital converter 9.

The control unit 10 controls pseudo-simultaneous charging of all batteries by multiplexing the current paths going through each of the switches S_{11} up to S_{nl}. The multiplex cycle ranges from about 1ms up to 10ms multiplied by the number of

batteries n. As a consequence, the breakdown of the energy reservoir into n batteries does not extend the charging time since the overall charging current delivered is n times the charging current of any individual battery.

With reference to each of the timing diagrams shown in Figures 2, 3 and 5 a logic "high" with respect to each switch means the switch is closed. Shown in Figure 2 are various timing diagrams showing current versus time of an instance of pseudo-simultaneous charging of two batteries. It is to be noted that any number of batteries can be charged in such a fashion. Switch 5a is closed for a period of t_1 which causes the current in inductor 5b to constantly rise. Subsequently switch 5c in the input voltage converter circuit 5 closes for a period of t_2 (while switch 5a is open) which causes the inductor 5b to discharge and thereby making the current therethrough decrease. Periods t_4 and t_5 are non-overlapping times that allow the current in inductor 5b to decrease and to avoid parallel connection of batteries due to control signal delays. It is noted that for switch S_{11} this is closed to enable current to flow through to battery B_1 and the current in that battery accordingly follows the current profile going through the inductor 5b over the period. The period t_3 is the multiplex period which can be multiples of the inductor charging cycles. Throughout the period t_3 it is noted that switch S_{21} is open and therefore no current flows through to battery B_2. Once the second pulse in period t_3 pertaining to switch 5c closing finishes, in other words at the start of the period t_4 where switch 5c is open there is a delay across that period t_4 for the switch S_{11} to open. Subsequently, in the next cycle when switch 5a is closed to let current flow through the inductor 5b, switch S_{21} is closed to enable current to flow through to battery B_2 of which the current profile follows that of the current through inductor 5b in accordance with the opening and closing of switches 5a and 5c.

The control unit 10 also controls pseudo-simultaneous discharging of the batteries B_1 through to B_n in order to optimise the system for an optimum working regime of the batteries. During discharge, the battery associated switches S_{12}... S_{n2}, serve as multiplex switches as well as charge switches for the output converter inductor 7b. In this case the multiplexing among the switches is controlled by control unit 10 and the duration of the charge time for inductor 7b is controlled by switch control unit 7a. Thus whichever battery B_1 up to B_n is discharging will have its respective output arm of each switch closed, for example S_{12}, S_{22} up to S_{n2}. During discharge, the control unit 10 decrements automatically the bit vectors in the battery status register 11 representing the SOC of each individual battery according to the voltage drop across

shunt resistor 12. Thus a digital bit value represents the state of charge of each battery at a particular time, whether that battery has discharged or not. If the SOC of any individual battery falls below the optimum regime, for example a second percentage limit, as discussed above, the discharge process of this specific battery is terminated.

5   In Figure 3 there is shown a timing diagram of current versus time of pseudo-simultaneous discharging of two batteries. Period t_3 is the multiplex rate which can be multiples of inductor charge cycles $t_1 + t_2$. Thus it can be seen with switch S_{12} closed current discharges from battery B_1 increasing up to a point when the switch is opened and subsequently in period t_2 switch 7c is closed whereupon the current discharging for battery B_1 decreases to a point when switch 7c opens and switch S_{12} closes at the end of period t_2. The current flowing through the inductor 7b follows the discharge current profile from battery B_1, as long as switch S_{12} is closed. During all of this time t_3, the other switches remain open and in particular switch S_{22} and therefore no current is being discharged from the battery B_2 as shown. In the next discharging cycle the switch S_{22} is closed to enable current to be discharged from battery B_2 through the inductor 7b as shown in the next sequence or time period in Figure 3.

         The control unit 10 periodically checks for consistency between the voltage and SOC of each individual battery. Each battery features a specific voltage-charge characteristic, depending on cell chemistry. If, for instance, a particularly designed Li-Ion cell has a nominal voltage between 3.4 and 3.6V at 50% SOC when discharged with a current of 5mA, consistency is recognised by the control unit 10 if the above conditions are verified. If, for instance, a cell voltage of only 2.5V is verified, corresponding to a typical lowest working voltage of a carbon/lithium cobaltate lithium ion battery with a copper current collector used in the negative (carbon) electrode, then control unit 10 judges that the battery is defective and marks a specific battery disable flag in the battery status register 11. As a consequence, the battery is kept isolated for the rest of its lifetime and is omitted from charging and discharging cycles.

         A further embodiment of the invention is shown in Figure 4. Like reference numerals apply as in Figure 1. The main difference between the embodiments shown in Figure 4 and Figure 1 is that in Figure 4 a different switching arrangement allows a reuse of the original input voltage converter inductor 5b for the output voltage converter circuit 7 as well. In other words rather than using the inductor 7b in the output voltage converter circuit 7 of Figure 1, this is now incorporated into a single inductor 5b for input and output conversion of voltages. Thus both terminals of the

inductor 5b are respectively connected to the output (implant) circuit, such as an implantable hearing prosthesis circuit like a middle ear implant or cochlear implant, through respective switches 5d and 5f. A switch control unit 5e controls the switches 5a, 5c, 5d and 5f.

5   The main reason for using a single inductor for input and output voltage conversion is that inductors are generally bulky and consume a lot of space on a circuit board and are generally expensive devices in comparison to other devices. Particularly in implantable devices, space is scarce and therefore a refined embodiment is utilised in the circuit arrangement of Figure 4. During charging, the inductor 5b can be used

10   simultaneously for both converting the input voltage to charge the batteries B_1 up to B_n and for converting the battery voltage to feed the cochlear implant circuit. An uninterrupted power supply of the implant circuit is granted through dispersing discharge cycles and charge cycles. The functions of the other components shown in the circuit arrangement of Figure 4 are similar to those as in Figure 1.

15   With reference to Figure 5 there is shown a timing diagram of current versus time of a period of operation of the input/output converter switches where, for instance, battery B_1 is charged through switch S_1 and battery B_2 is discharged through switch S_2.

As can be seen in Figure 5 with switch 5a closed it allows current to flow through the inductor 5b, indicated by current I_L and switch S_1 is closed thereby

20   charging battery B_1. The switch 5a is closed during the time interval t_1, and the switch 5c is opened during time interval t_1. At the end of time interval t_1, i.e. at the beginning of time interval t_2, the switch 5a will be opened and the switch 5c closed. The current through the inductor 5b is slowly discharged to ground during t_2, however switch S_1 remains closed until time t_3 expires when the switch 5c is open again. A new charging

25   or discharging cycle then starts after time t_4 whereby switch 5d is closed as is switch S_2. Thus battery B_2 is discharging current through the inductor 5b in a reverse direction to be output to the implant circuit. Thus the current I_L being the current through the inductor 5b is shown with a negative polarity increasing while switch S_2 is closed. At this time switch 5f is closed thereby discharging the current I_L back to ground. Thus

30   switch 5d remains closed for the entire duration for which switch S_2 and switch 5f are closed.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly

35   described. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.